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Pion, Light Fragment and Entropy Production in Nuclear Collisions*

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Abstract

The production of pions and light fragments in fast nuclear collisions is calculated in a relativistic fluid dynamical model. The linear bombarding energy dependence and, in particular, the absolute values of the calculated pion, proton, and deuteron yields are found to be in agreement with recent experimental data. The previous discrepancy between the calculated entropy values and the measured deuteron-to-proton ratios is resolved.

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The bombarding energy dependence of the pion and light fragment production has been measured recently for central collisions of equal mass nuclei.[1,2] Such experiments are of great interest for several reasons: Fluid dynamical calculations show some sensitivity of the pion excitation function to the nuclear equation of state[3-5]; in particular, the increase in entropy due to a phase transition in dense nuclear matter (pion condensates, density isomers) can result in a threshold increase of the pion excitation function.[3] Also, the deuteron-to-proton ratio, d/p, carries information on the entropy produced in the collision.[5-7] A fluid dynamical description of high energy nuclear collisions requires the incident energy and longitudinal momentum to be rapidly randomized, so that local thermal equilibrium is established. Calculations based on a transport theory indicate[8] equilibration times $\tau_{CM} \sim$ 3-4 fm/c $\sim$ 1-1.3 10^{-23} s in the bombarding energy range E_{LAB} = 0.2-2.1 GeV/n, which is shorter than the collision time R/V $\sim$ 10-20 fm/c. Deviations from local thermal equilibrium can be treated phenomenologically in the fluid dynamical model by incorporating the nuclear viscosity.[3,9,10] Fully three-dimensional fluid dynamical calculations[11,12], which did not take into account viscosity, as well as one- and two-dimensional viscous calculations[3,9,10] have shown that in the bombarding energy range of interest (E_{LAB} = 0.1-2.1 GeV/n) the nuclear matter is strongly compressed and highly excited during the early stage of the collision. The calculated densities, ρ, and temperatures, T, in this stage agree well with the solution of the relativistic Rankine-Hugoniot equation[3], $W^2 - W_0^2 + p(W/\rho - W_0/\rho_0) = 0$, used in the present work to compute ρ and T. Here $W_0 = m_N c^2 - B_0 \approx 931$ MeV and $\rho_0 = 0.17$ fm^{-3}. This agreement is natural since this equation simply expresses the conservation of baryon, momentum, and energy fluxes across the shock front. Even a substantial spreading of the width of the shock front due to a large viscosity does not influence the state of the shocked matter behind the shock front[3,9,10]. The internal energy per nucleon, $W(\rho,T) = W_0 + E_C(\rho) + E_T(\rho,T)$, is composed of a compression energy $E_C(\rho)$, for which we use $E_C(\rho) = K/18\rho\rho_0\ (\rho - \rho_0)^2$ or $\tilde{E}_C = E_C\ \rho/\rho_0$, respectively [from here on referred to as the linear (ρ) and quadratically (ρ^2) increasing $E_C(\rho)$], with the compression constant K = 200 MeV, and a thermal energy $E_T(\rho,T)$, for which the nonrelativistic Fermigas formula is used. The pressure $p(\rho,T)$ is connected to $W(\rho,T)$ via[3] $p = p_C(\rho) + \frac{2}{3}\rho E_T$. The internal energy in the shock zone, $W(\rho,T)$, is fixed by the lab kinetic energy per nucleon, E_{LAB}, as $W(\rho,T) = \gamma_{CM}(E_{LAB})\ W_0$, where $\gamma_{CM} = (1 + E_{LAB}/2W_0)^{1/2}$. The entropy per nucleon, S, in the compressed system can well be approximated by the low-temperature Fermigas expansion[7] for $E_{LAB} < 400$ MeV/n, while the classical Boltzmann gas approximation[6] results systematically in too small values of the entropy: S_B is even <u>negative</u> for $E_{LAB} < 120$ MeV/n! Therefore, we use the exact fermigas expression[5] S(x), which depends only on the quantity $x = E_T\rho^{-2/3}$.

From the compressed state, the system expands because of the internal pressure. As the shock compression is the only mechanism for entropy production in a perfect (nonviscous) fluid, the entropy would be conserved during the decompression stage and (ref. 5-7,11,12) $E_T^{exp}\ (\rho, S = \text{const}) = E_T^{initial}\ (\rho/\rho^{initial})^{2/3}$. However, Csernai and Barz[9] have demonstrated that the viscosity has important effects on the expansion stage: because of the friction, part of the energy is taken out of the fluid motion and is restored in internal excitations. In particular, viscous effects increase the entropy of the fluid during the expansion by a factor[9] $\eta = S_\eta/S_s \approx 1.2$. Here S_s is the entropy in the compressed stage and S_η is the entropy after the viscous expansion.

Figure 1 shows the trajectories $T(\rho)$ for the compression and subsequent expansion for various bombarding energies and two different equations of state. As the incident energy is raised, the density and temperature increase. During the subsequent decompression phase the temperature depends on the viscosity (shaded areas). The isentropic expansion yields lower temperatures than the viscous expansion. The linear increasing $E_c(\rho)$ results in higher densities and temperatures than the stiffer quadratically increasing $E_c(\rho)$ at any given bombarding energy. However, note that the temperatures at any given density during the expansion depend only slightly on the particular choice of $E_c(\rho)$. This is because the total entropy produced is rather insensitive to the equation of state.[7] For example, S = 3.3 and 3.35 at E_{LAB} = 0.8 GeV/n for the linear (ρ) and quadratically increasing (ρ^2) equation of state, respectively. Only at lower energies, E_{LAB} < 0.2 GeV/n, is there a larger influence of $E_c(\rho)$ on the amount of entropy produced.[7]

In the expansion, the fluid eventually reaches the break-up density,[13-15] $\rho_{BU} \sim 0.7\rho_0$, at which the thermal equilibrium can no longer be maintained. At this freeze-out moment, the number of pions and composites is calculated by equating the baryon number and the internal energy of the nuclear fluid with that of a relativistic quantum gas of noninteracting particles in chemical equilibrium.[14,15] Calculations based on transport theory indicate that chemical equilibration can indeed be reached towards the freeze-out time.[13,14] The particles included in the present calculation are[15] π, Δ, p, n, d, t, ^{3}He, ^{4}He, and d*,

$^{4}H^*$, $^{4}He^*$, $^{5}He^*$, $^{4}Li^*$, $^{5}Li^*$. The asterix denotes particle unstable excited states of the nuclei, which decay after the breakup together with the Δ's by particle emission into pions, nucleons, and stable light nuclei.[14,15] [A* → (A - 1) + nucleon.]

It is essential to point out that the experimentally observed stable particles can arise in two distinct ways: either they are already present in the chemical equilibrium phase or they are produced subsequently from the decay of the particle unstable resonances (nuclear and baryonic). We will show below that this second source of stable particles can have a profound effect in the observed d/p ratio.

Figure 2 shows the mean number of negative pions per charged participant particle, $\langle n_{\pi^-}\rangle/\langle Q\rangle$, measured in high multiplicity selected ("central") collisions of ^{40}Ar + KCl over a wide range of bombarding energies[1]. Here Q is defined in accord with ref. 1 as $\langle Q\rangle = \Sigma - 2\langle n_{\pi^-}\rangle$, where Σ is the mean total number of charged participants. Also shown are the measured large angle inclusive π^-/Z ratios[2], where Z is the total number of positive charges in reactions of ^{40}Ar + KCl and ^{20}Ne + NaF. Linear cascade calculations[16] fail in reproducing the absolute values and the observed linear dependence of $\langle n_{\pi^-}\rangle/\langle Q\rangle$ on the bombarding energy. The calculations in the nuclear fireball model shown in Fig. 2 (dotted line) and in the phase space model[17] yield absolute values of $\langle n_{\pi^-}\rangle/\langle Q\rangle$ being too large by a factor of $\gtrsim 3$.

In contrast, the absolute values of $\langle n_{\pi^-}\rangle/\langle Q\rangle$ calculated in the present work as well as the linear energy dependence agree remarkably well with the data (see Fig. 2). Also shown are the results of the perfect fluid calculation, $\eta = 1.0$, which underestimates the pion production rates.

Another quantity of interest is the π^-/π^+ ratio.[2,18] We find $\pi^-/\pi^+ = 1.38$ for Ar + Ca at 1 GeV/n, in agreement with the experimental data[2,18] $\pi^-/\pi^+ \approx 1.4$. These results demonstrate that compression and viscous effects are consistent with the observed pion data.[1,2,18]

As a further test of the present model, we now compute the yield of light nuclei. It was suggested by Siemens and Kapusta[6] that the deuteron-to-proton ratio, $R_{dp} \equiv \langle d\rangle / \langle p\rangle$, can be used to determine the entropy per baryon, S, produced in the collisions via

$$\text{"S"} \equiv 3.95 - \ln R_{dp} \qquad (1)$$

This formula is derived for an ideal classical gas of nucleons assuming $R_{dp} \ll 1$. Figure 3 shows the "entropy" values, "S", extracted from the data[2] via eq. (1) in comparison to the entropy calculated in the present model. The calculated entropy S_η tends towards the experimental data at high energies $E_{LAB} \gtrsim 2$ GeV/n. At low energies, however, the observed "entropies" tend towards a constant value "S" ≈ 5, while S_η and S_s naturally drop to zero for $E_{LAB} \to 0$. This seems to indicate an unusual mechanism for entropy production.[6]

On the other hand, our calculated $\langle d\rangle / \langle p\rangle$ ratios are in good agreement with the measured values[2], $R_{dp} \approx 0.25$. To resolve this apparent paradox, we show in Fig. 3 the "entropy", "S", obtained from the calculated R_{dp} values via eq. (1). Note the good agreement between the curves and the data[2]. Also note that the calculated "S" ≈ 5 at E_{LAB} 100 MeV/n! In fact, experiments in the intermediate energy region, 15 MeV/n $\lesssim E_{LAB} \lesssim$ 100 MeV/n, consistently report[19] deuteron-to-proton ratios $R_{dp} \approx 0.3$, just as predicted by the present calculation. We find that this is due to the decay of particle unstable excited nuclei, which become increasingly important at intermediate and low energies. In fact, the resonance decay products dominate the chemical equilibrium contribution,

$$\langle p\rangle_{\text{observed}} = \langle p\rangle_{\text{equil.}} + \langle p\rangle_{\text{decay}}, \qquad (2)$$

with $\langle p\rangle_{\text{decay}} > \langle p\rangle_{\text{equil.}}$ for $E_{LAB} < 400$ MeV/n. Hence, we conclude that the connection between the entropy and R_{dp} is not given by eq. (1).

In this letter we have presented relativistic viscous fluid dynamical calculations on the production of pions and light fragments in high energy nuclear collisions. The calculated linear bombarding energy dependence and, in particular, the absolute values of the $\langle n_{\pi^-}\rangle/\langle Q\rangle$, π^-/π^+, and $\langle d\rangle/\langle p\rangle$ ratios agree well with the experimental data. The shapes of the pion, proton, and deuteron spectra can also be understood in the fluid dynamical model.[5,9,20] This agreement provides further evidence for compression effects in fast nuclear collisions. Very precise data and calculations will be necessary, however, to determine accurately the equation of state in the future.

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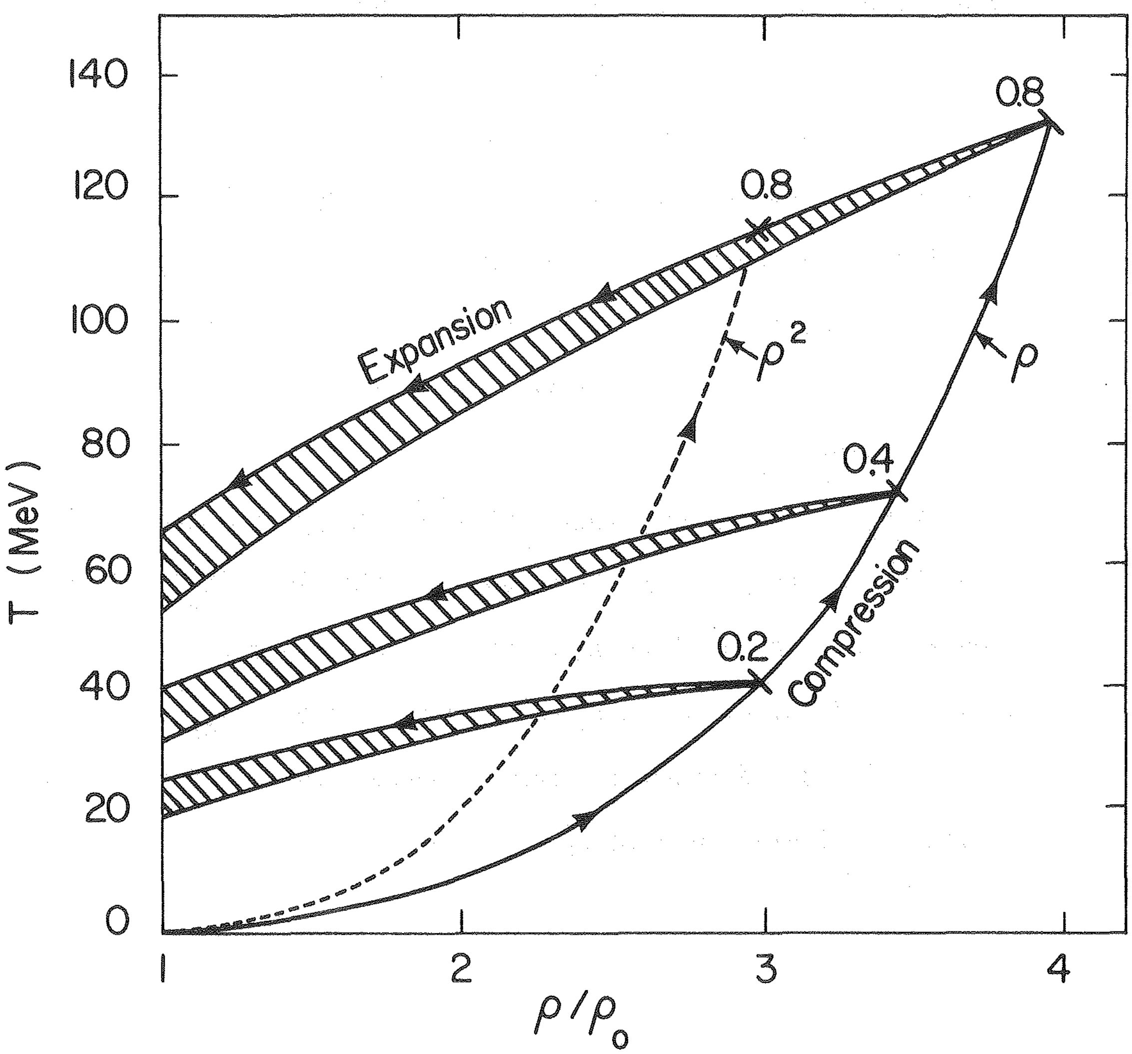
Figure Captions

Fig. 1) The trajectories $T(\rho)$ of the hydrodynamical compression and expansion of the matter are shown for $E_{LAB} = 0.2, 0.4, 0.8$ GeV/n. The shaded areas indicate the temperature increase due to viscosity. $T(\rho)$ using two different equations of state, ρ (solid curve) and ρ^2 (dashed) are shown.

Fig. 2) The bombarding energy dependence of the average number of pions per emitted charged nuclear fragment, $\langle n_{\pi^-} \rangle / \langle Q \rangle$, is compared to the fireball model (FB, dotted line) and to the present calculation. The solid (dashed) lines are for $\rho_{BU} = 0.7$ (1.0) ρ_o, respectively.

Fig. 3) The bombarding energy dependence of the entropy is shown as calculated for the viscous (S_η) and inviscid fluid (S_s). Also shown are the "entropy" values, "S", obtained from the measured[2] and calculated deuteron-to-proton radios R_{dp} via eq. (1). The solid (dashed) lines represent the viscous (inviscid) calculation with $\rho_{BU} = 0.7\ \rho_o$.



XBL 813-427

Fig. 1

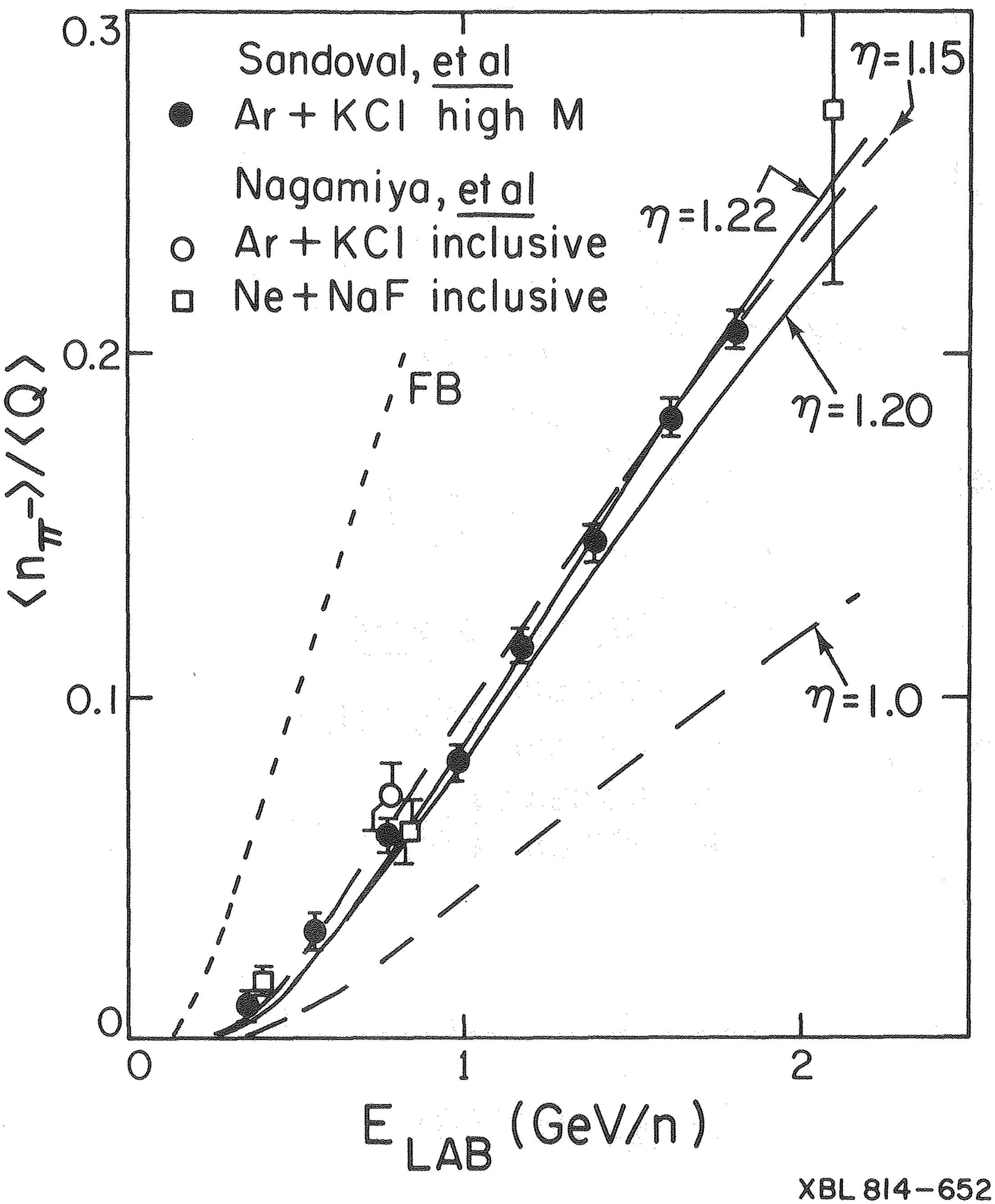

Sandoval, et al
Ar + KCl high M
Nagamiya, et al
Ar + KCl inclusive
Ne + NaF inclusive
η=1.15
η=1.22
η=1.20
η=1.0
FB
$\langle n_{\pi^-} \rangle / \langle Q \rangle$
0.3
0.2
0.1
0
1
2
E_{LAB} (GeV/n)
XBL 814-652

Fig. 2

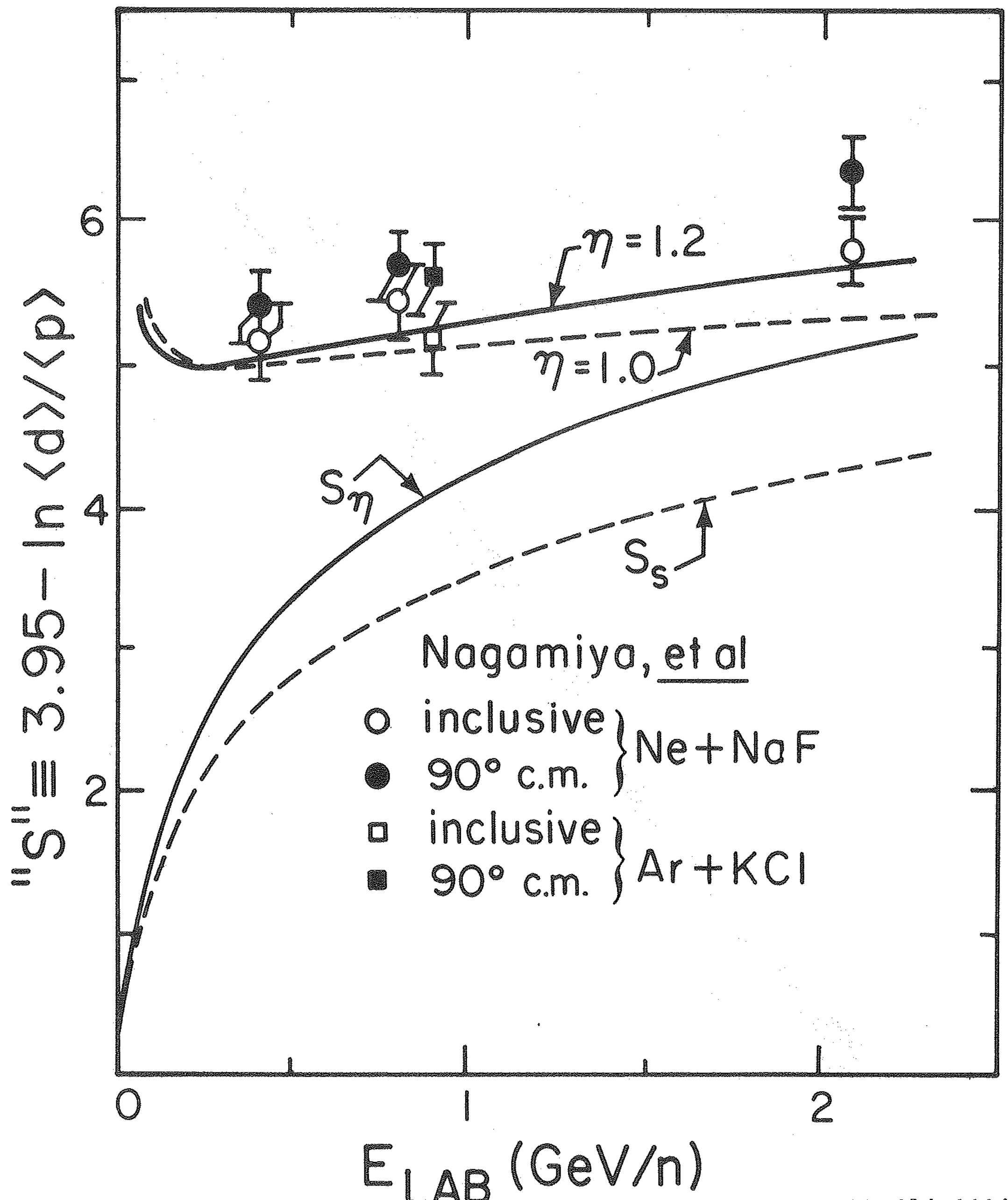


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Fig. 3